20 METER SOLAR SAIL ANALYSIS AND CORRELATION

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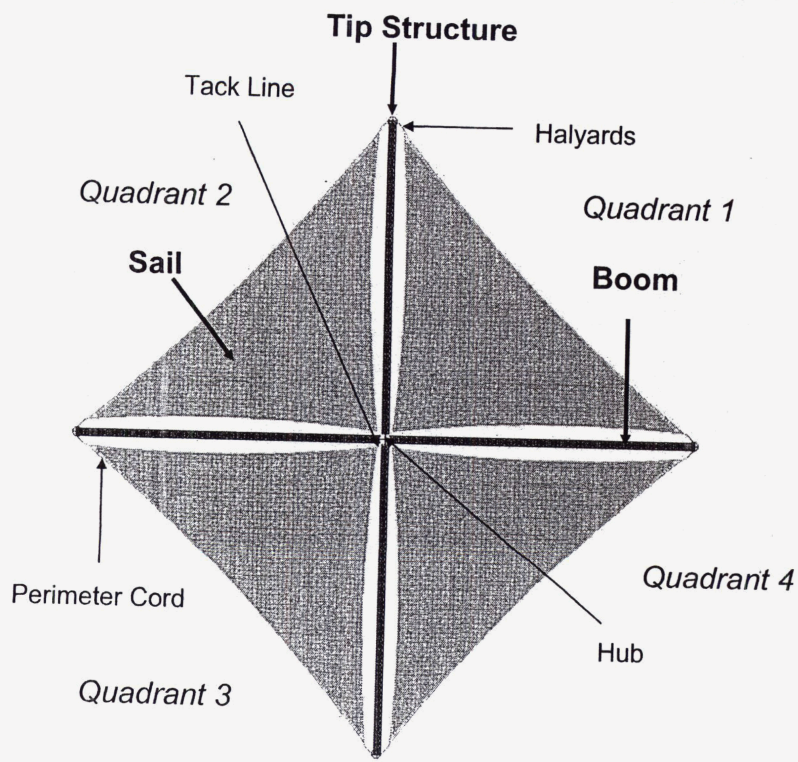
Outline

- 20 meter Solar sail FEM
- Mesh Density Study
- Static Shape Optimization
- Static shape test/Analysis correlation and results
- System Dynamics test/analysis comparison
- Conclusion

20 Meter System Overview



The 20 meter system consists of three primary components:

- Booms
  - Longerons
  - Battens
  - Pre-tensioned Diagonals
- Sails
  - Reflective sail area
  - Shear compliance border
  - Cord
  - Targets
- Tip Structure

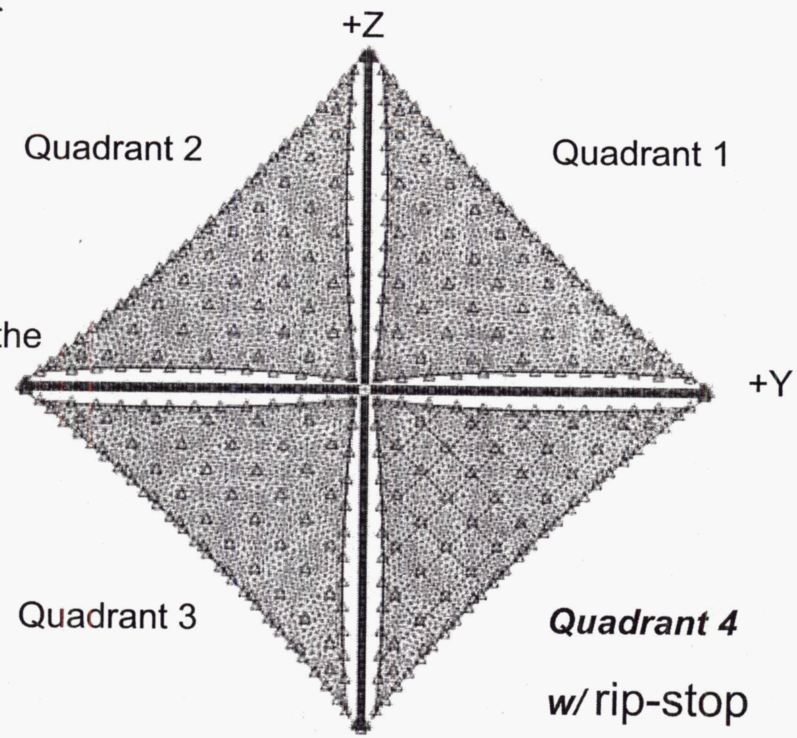
The hub structure is omitted to reduce model complexity

Base, CP1 Polymer Aluminum Coating Composite Properties Aluminum Coating	Density	Modulus			Thickness	
	lb/in^3	E (psi)	G (psi)	Poisson	(m)	(in)
Quadrant 1	0.053	588,850	223,971	0.315	0.00000277	0.000109
Quadrant 2	0.053	588,850	223,971	0.315	0.00000308	0.000121
Quadrant 3	0.053	588,850	223,971	0.315	0.00000354	0.000139
Quadrant 4	0.053	588,850	223,971	0.315	0.00000323	0.000127

Analytical Model Overview

20 Meter Solar Sail System, Finite Element Model

- The system model includes four sails, and four masts
  - The hub structure is removed to simplify the model
    - Early analysis determined the hub is very stiff relative to the structure, so it was removed from the model without significant loss of accuracy
  - The four sails use the same mesh, but with different properties
    - Thickness, modulus and density were set based on material samples
    - Distributed mass was added to the sail quadrants to match tested sail weights
    - Point masses are only used for sail targets (sequencers, grommets, etc. are included in the distributed mass)
  - The masts are deployable truss structures (see AIAA-2005-2123)
  - 7529 total nodes (45K DoF)
  - 15750 total elements



Sail Finite Element Model

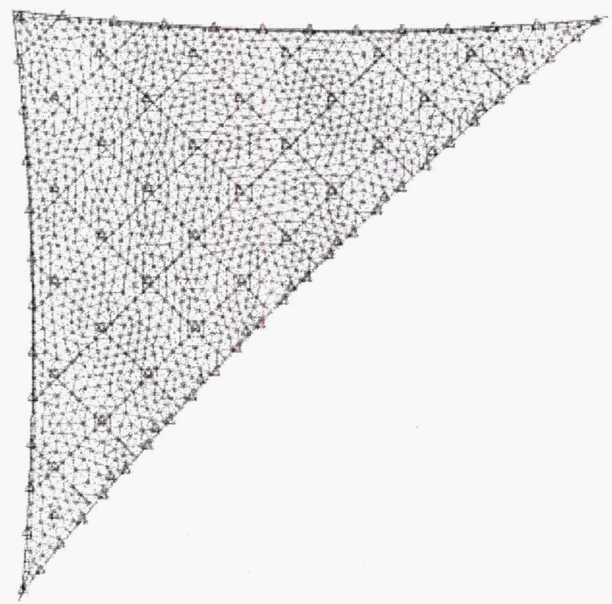
The Sail Finite Element Model

- Quadrant 4 shares basic mesh with other quadrants
  - Sail elements are membrane only utilizing the TRIA3 element
  - Shear compliant border is modeled with bar elements
  - Targets are point masses connected to the sail mesh by MPCs
- Quadrant 4's model includes rip-stop elements
  - Rip-stop elements are modeled with CBEAM; they have bending stiffness
  - Seam rip-stop elements include stiffness of overlapping material

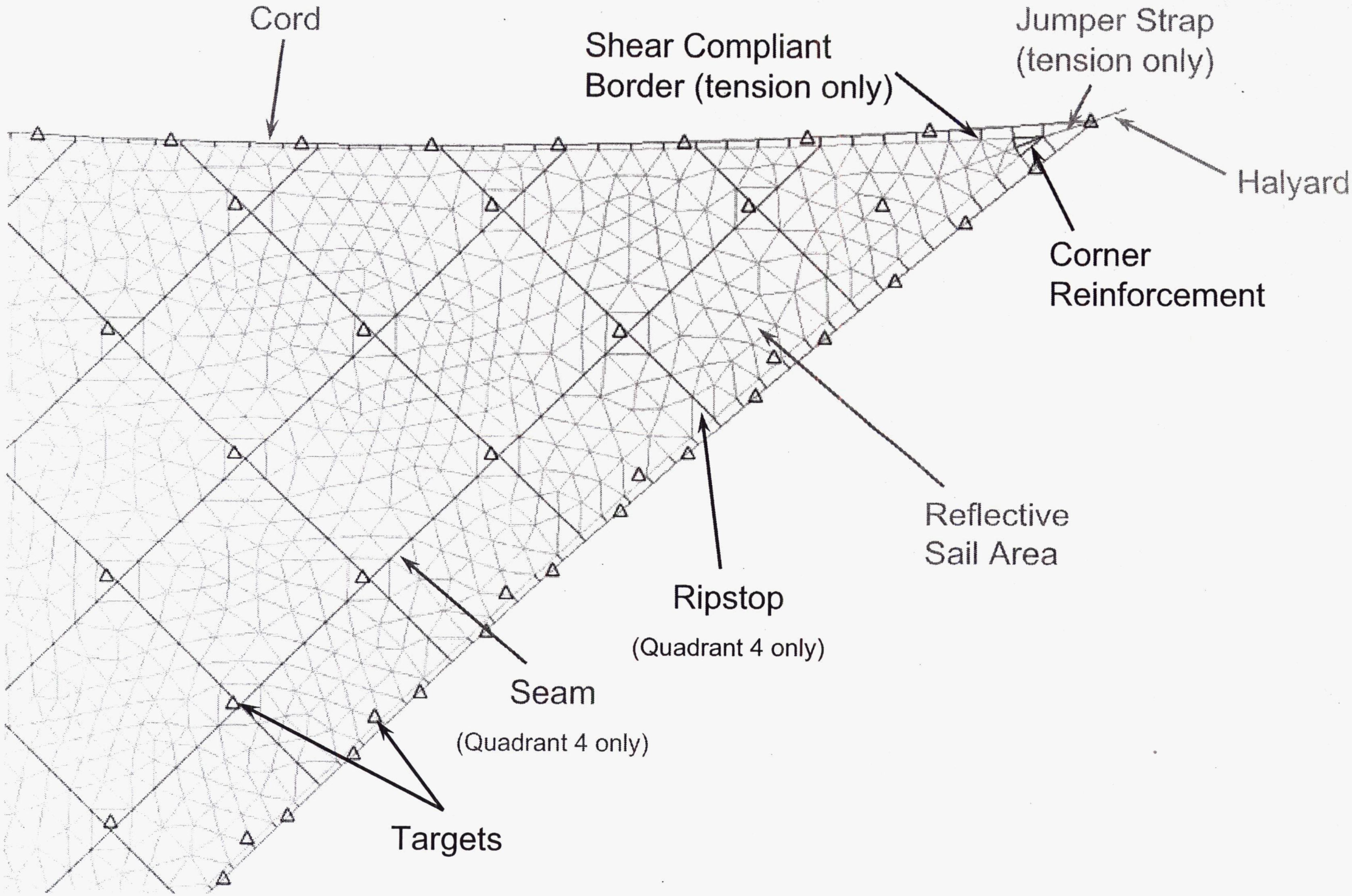
1614 Nodes

3345 Elements

- 2510 Sail Area (TRIA3)
- 90 Targets (CONM)
- 179 Cord (CBEAM)
- 175 Shear Compliance (CROD)
- 386 Rip-stop (CBEAM)
- 3 Jumper Straps (CBEAM)
- 2 Halyard (CBEAM)



Sail Finite Element Details



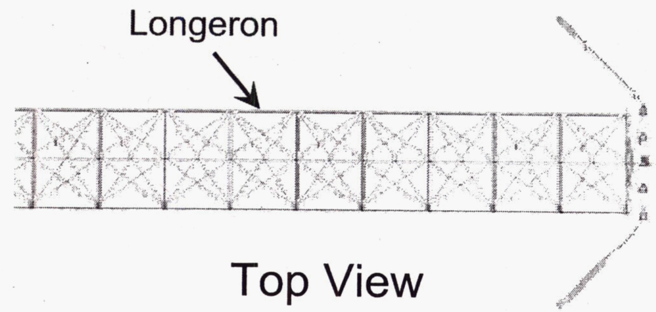
Mast / Mast Tip Model

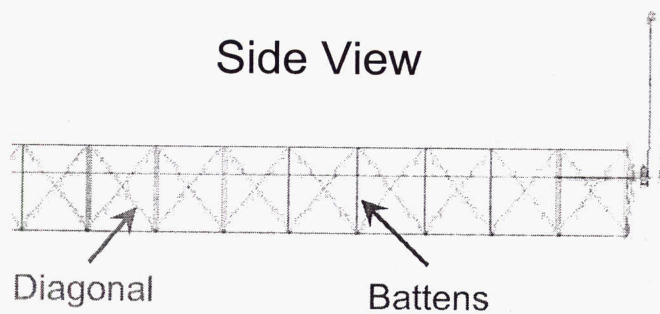
Mast Modeling

- The mast consists of three types of elements
  - Longerons - Composite beams running the length of the mast (CBEAM)
  - Battens - Composite rods maintaining the mast's cross-section (CROD)
  - Diagonals - Pre-tensioned cables providing shear strength (CROD)
- Distributed mass on the longerons is used for miscellaneous non-structure weight (i.e. wiring, fittings, etc.)

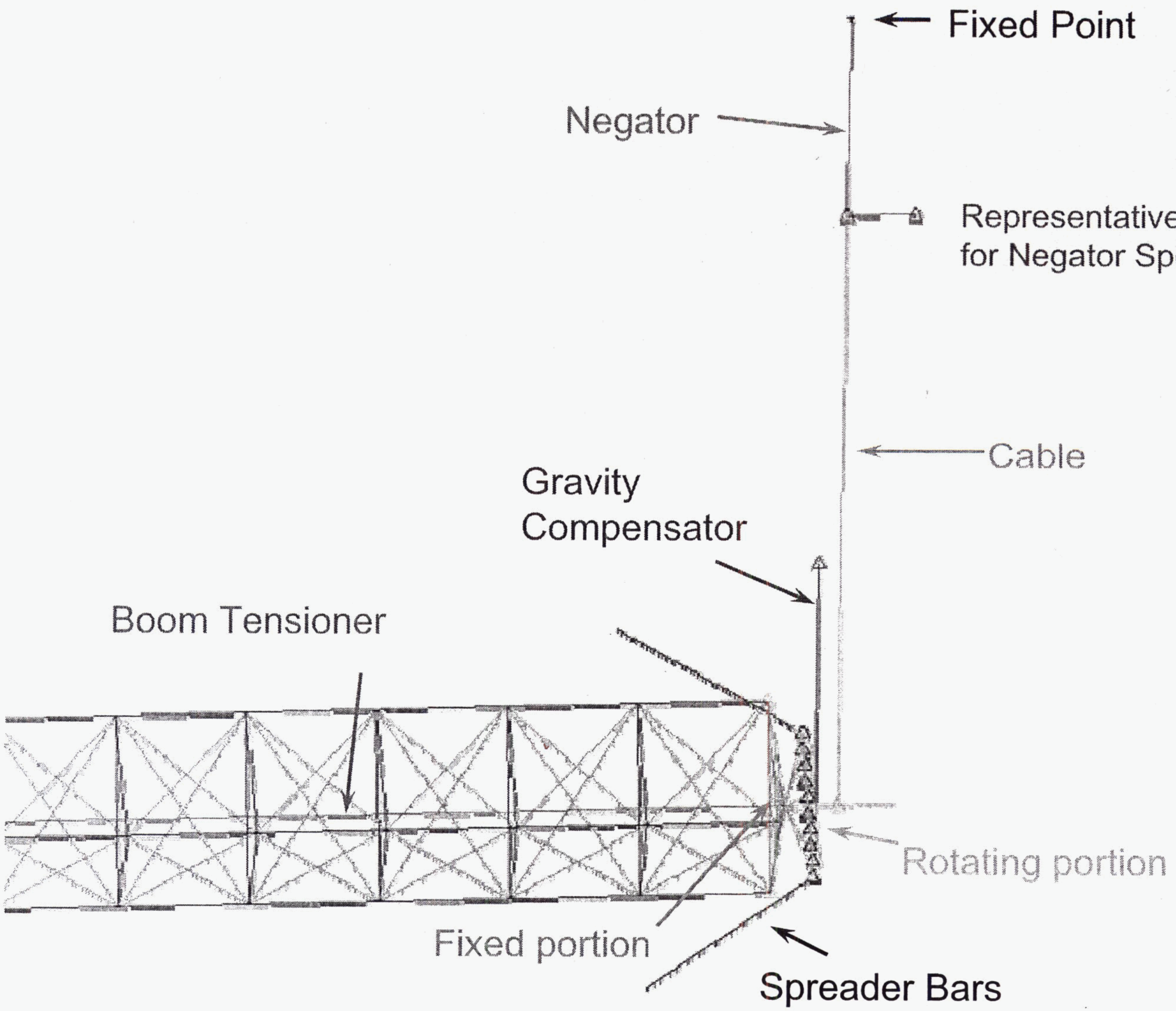
Mast Tip Modeling

- The Mast tip consists of four parts
  - Fixed portion which is attached to the end of the mast
  - Rotating portion which includes the spreader bars
  - Negator off-loading mechanism
  - Gravity Compensator
- Point masses are used to mimic weight distribution of tip structure





Mass Tip Details



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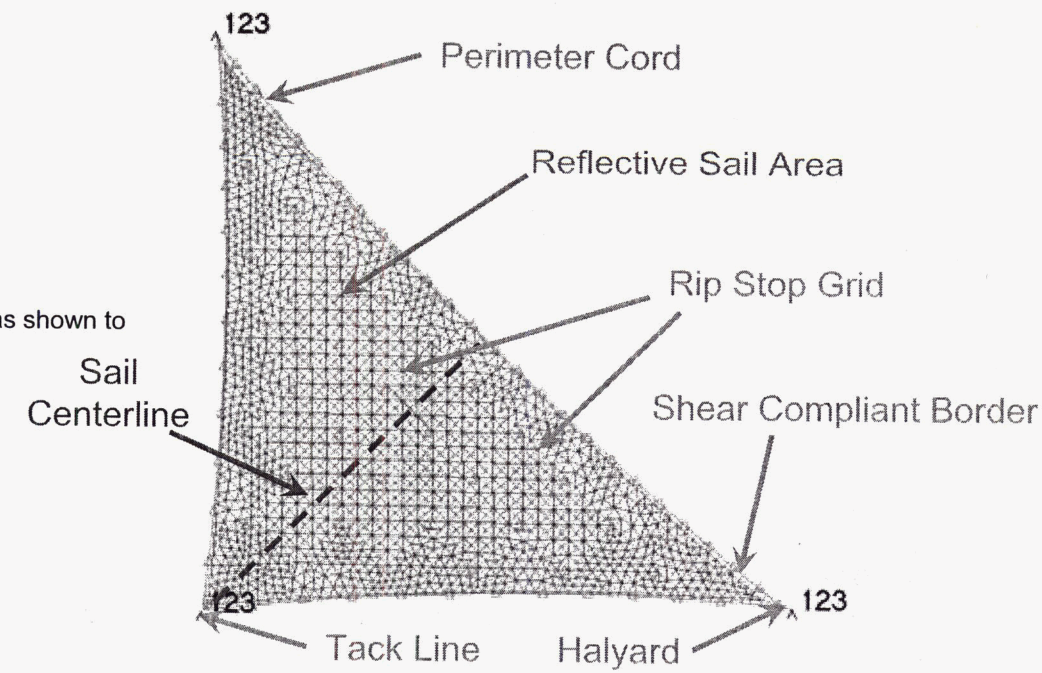
Mesh Study Overview

Objective: Determine the element type and size that best represents a 20-meter solar sail under ground-test (Gravity) load conditions.

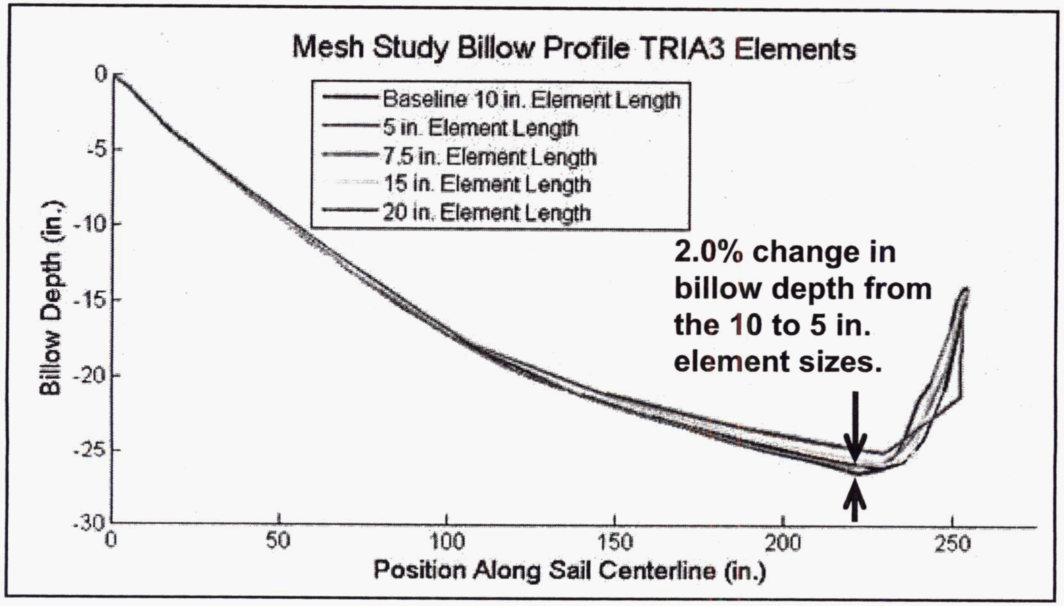
Procedure: Compare displaced sail shape from eight different finite-element mesh configurations as listed below.

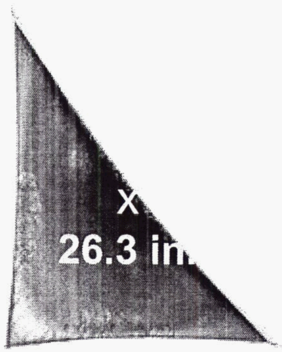
1. 5 in. edge length, TRIA3 elements
2. 7.5 in., TRIA3
3. *10 in., TRIA3
4. 15 in., TRIA3
5. 20 in., TRIA3
6. 10 in., QUAD4
7. 20 in., QUAD4
8. 30 in., QUAD4

*Indicates the baseline triangular mesh configuration as shown to the right

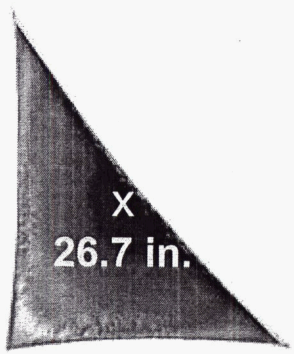


One Quadrant Deflection due to Gravity
TRIA3 Mesh

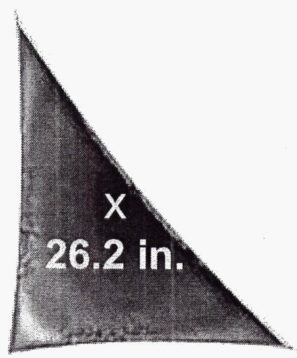




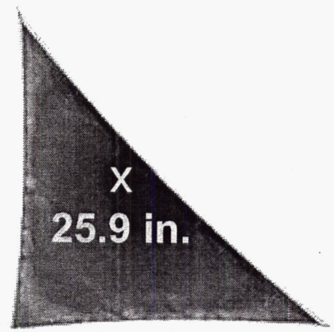
5 in. element length



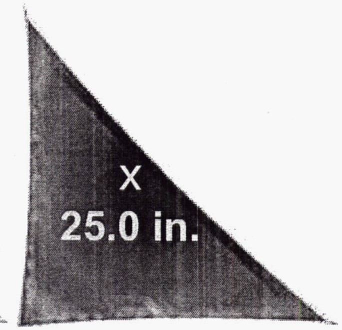
7.5 in.



Baseline 10 in.

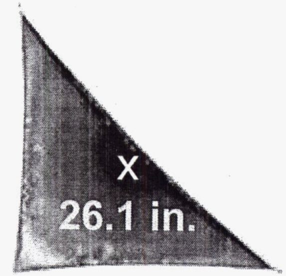


15 in.

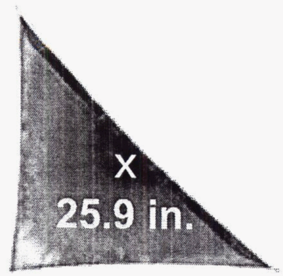


20 in.

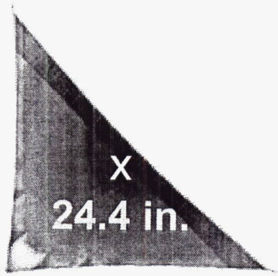
One Quadrant Deflection due to Gravity
QUAD4 Mesh



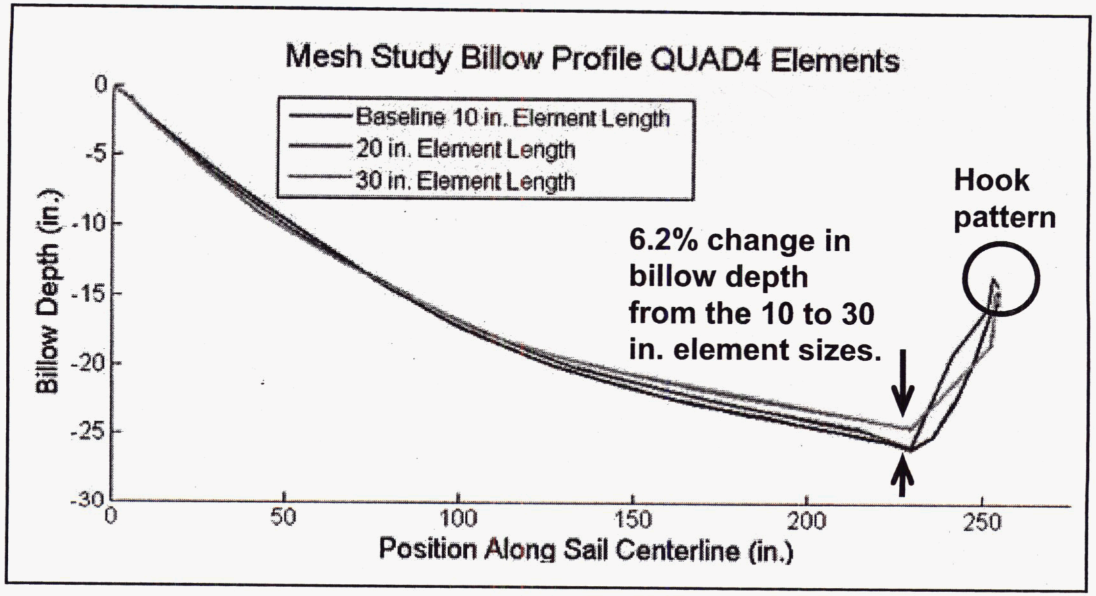
Baseline 10 in. element length



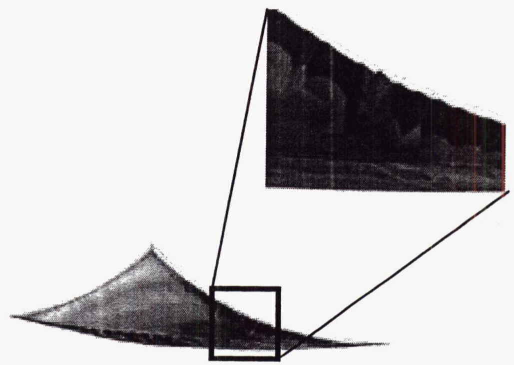
20 in.



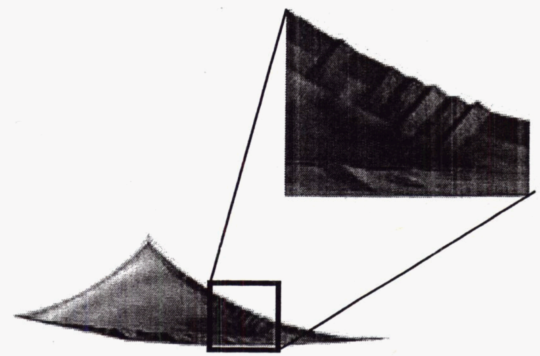
30 in.



The Hook pattern near the cord occurred when the peak of the wrinkle pattern forced the mesh (corner element) above the cord.

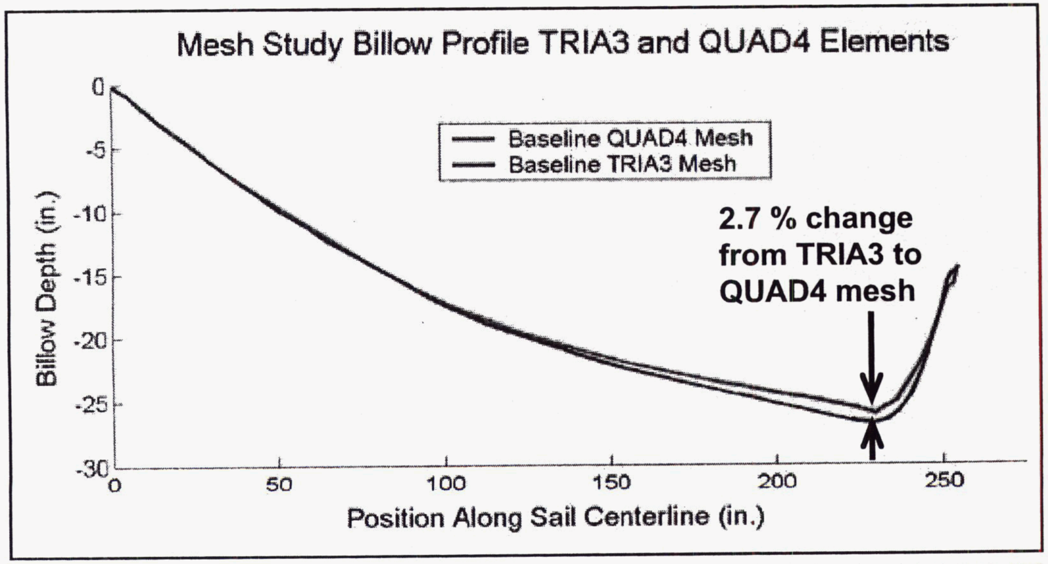


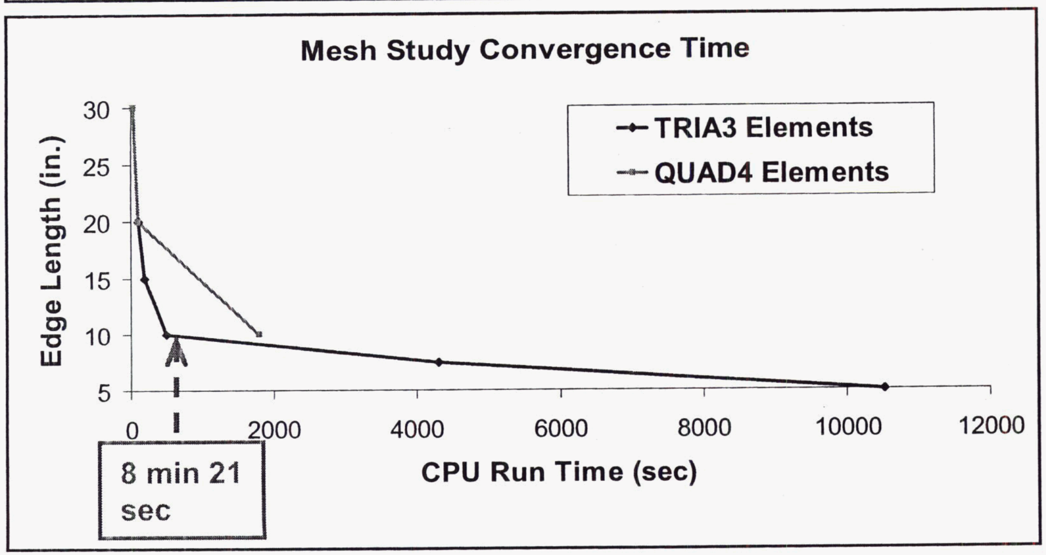
Baseline TRIA3 mesh



Baseline QUAD4 mesh

Mesh Study Conclusions





1. TRIA3 elements better represent wrinkle patterns than do QUAD4 elements.
2. Baseline, ten-inch elements are small enough to accurately represent sail shape as indicated by the small difference between the baseline and the 5 in. centerline profiles.
3. Baseline TRIA3 mesh requires a reasonable computation time of 8 min 21 sec.

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Static Shape Optimization

Examination of Quadrant 4 Only

- To simplify the model, only quadrant 4 was used in the analysis
  - Sail quadrants attach at 3 points and are thus statically determinant
  - Using a single quadrant greatly reduces run time and increases stability

Selection of Sail Parameters

- Only parameters that would have a significant impact on the shape were selected
  - Elimination of non-contributing parameters greatly reduces run times and total number of runs
  - Many parameters were eliminated based on previous work (AIAA-2005-2123)
- Parameters were also chosen based on unknowns from the test
  - I.e. The amount of sag in the jumper straps
  - The degree of uncertainty of a parameter determined the range

Static Shape Optimization - Parameters

Ten Parameters Were Varied During Optimization

- The two halyard loads were varied independently (2)
  - Nominal halyard load was 6 lbs.
  - Based on testing, halyard loads varied between 5 and 7 lbs.
- Halyard positions were varied, each in two directions (4)
  - Based on Photo-Grammetry (PG) data, the booms moved horizontally, vertically and in torsion
  - Each halyard was allowed to vary in z-direction, and in-plane perpendicular to its length
- Tack line position was varied vertically (1)
  - The position of the tack is well known relative to the structure, but the PG's reference plane was not well-established during the shape testing
- Jumper straps (total of 3 for Q4) amount of sag (3)
  - Jumper straps were designed with some sag. They are unloaded before sail tensioning, and carry load when the sail is deployed.
  - The straps were varied from no sag, to twice the nominal value

Optimization Methodology

Creation of a Response Surface

- 300 sail models were created with random parameters
  - For each model, the ten parameters were assigned a random value within their range
  - The parameters and the resulting target locations were saved for each run
  - These models form the response surface basis
- A response surface for *each* target was created
  - A moving least squares response surface was used
    - A moving least squares response only uses the results that are closest in parametric space, and weights them by distance
  - Rather than a response surface for the error, multiple response surfaces were created, one for each target
    - The error response surface is more prone to local minima/maxima
    - The target response surface has lower order behavior relative to parameters
    - Target response surfaces allow prediction of shape without running the model

Optimization Methodology

Optimize Parameters Based on Response Surface

- Run the optimizer on the response surfaces
  - Median Nastran job takes ~15 minutes to run and process
  - Thousands of response surfaces results can be processed in a minute
  - Can obtain a "best guess" set of parameters quickly
- Run a Nastran job with the "best guess" parameters
  - The response surface is a good estimate, but it will have prediction errors
  - Running the "best guess" model will provide actual displacement errors
- Incorporate the result back into the response surface basis
  - The result of the "best guess" job is included in the basis for the response surfaces
  - The response surfaces are recalculated
  - A new optimization is run on the updated surfaces
- Rerun optimizer with expanded response surface basis

Optimization Parameters

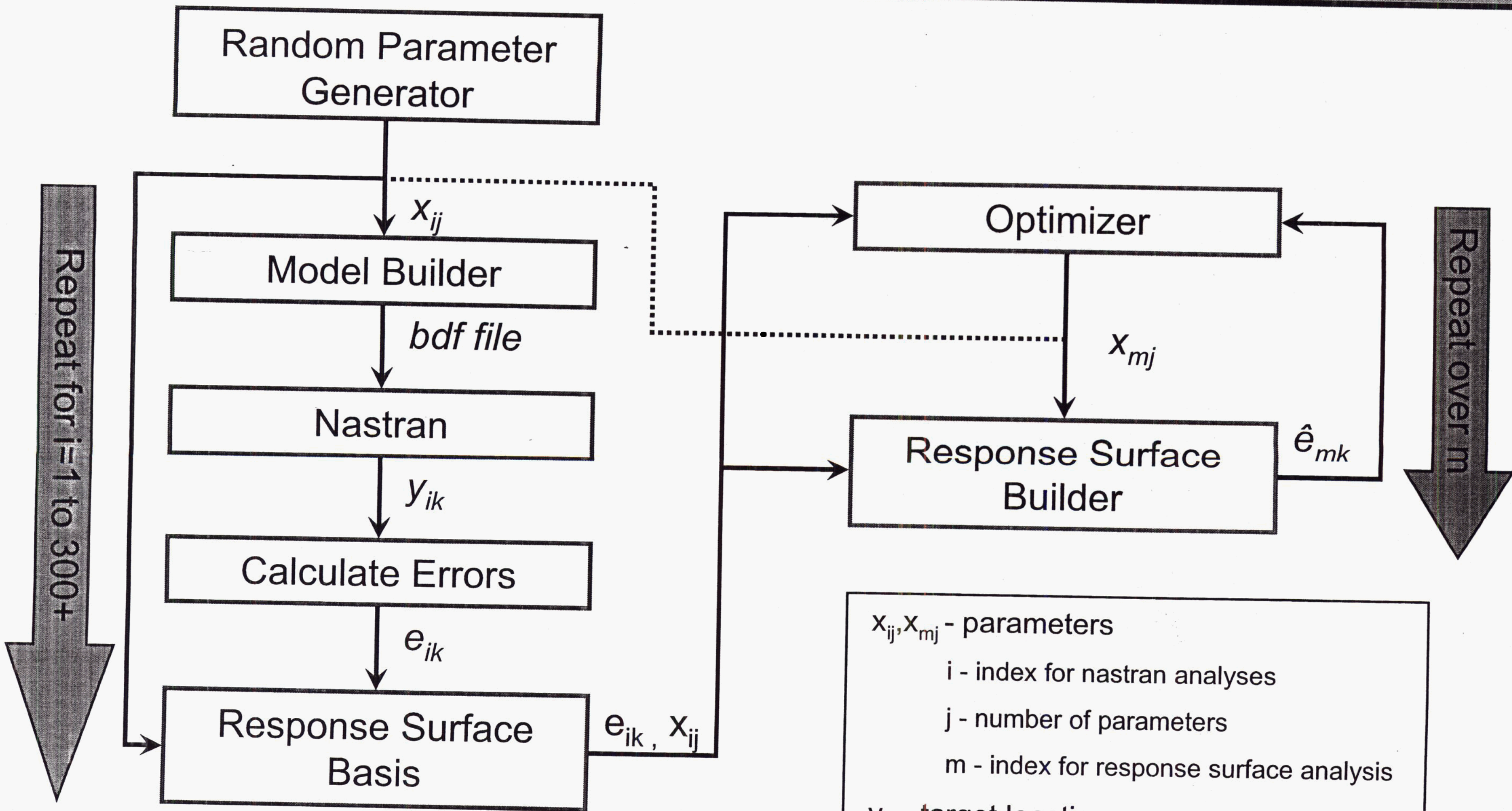
Optimization Parameters for the 0 degree spreader bar angle case

Parameter	Units	Estimated Minimum	Estimated Maximum	*Optimized Result*
Halyard Force +Y	lbs	5.00	7.00	*6.17*
Halyard Force -Z	lbs	5.00	7.00	*7.28*
Jumper Strap Slack +Y	inch (+ slack)	0.00	0.92	*-0.057*
Jumper Strap Slack -Z	inch (+ slack)	0.00	0.92	*-0.346*
Jumper Strap Slack Tack	inch (+ slack)	0.00	1.01	*0.142*
In-plane y-halyard motion	inch (+ inward)	-1.00	1.00	*0.713*
Vertical y-halyard motion	inch	-1.00	1.00	*0.851*
In-plane z-halyard motion	inch (+ inward)	-1.00	1.00	*0.977*
Vertical z-halyard motion	inch	-1.00	1.00	*0.154*
Vertical tack motion	inch	-0.50	0.50	*0.746*

Optimization Parameters for the 22.5 degree spreader bar angle case

Parameter	Units	Estimated Minimum	Estimated Maximum	*Optimized Result*
Halyard Force +Y	lbs	5.00	7.00	*7.00*
Halyard Force -Z	lbs	5.00	7.00	*7.15*
Jumper Strap Slack +Y	inch (+ slack)	0.00	0.92	*0.035*
Jumper Strap Slack -Z	inch (+ slack)	0.00	0.92	*-0.122*
Jumper Strap Slack Tack	inch (+ slack)	0.00	1.01	*0.156*
In-plane y-halyard motion	inch (+ inward)	-1.00	1.00	*0.361*
Vertical y-halyard motion	inch	-1.00	1.00	*0.517*
In-plane z-halyard motion	inch (+ inward)	-1.00	1.00	*0.929*
Vertical z-halyard motion	inch	-1.00	1.00	*0.249*
Vertical tack motion	inch	-0.50	0.50	*0.589*

Optimization Methodology



x_{ij},x_{mj} - parameters

- i - index for nastran analyses
- j - number of parameters
- m - index for response surface analysis

y_{ik} - target locations

- k - number of targets

e_{ik} - target errors

$\hat{e}_{mk}$ - estimated target errors

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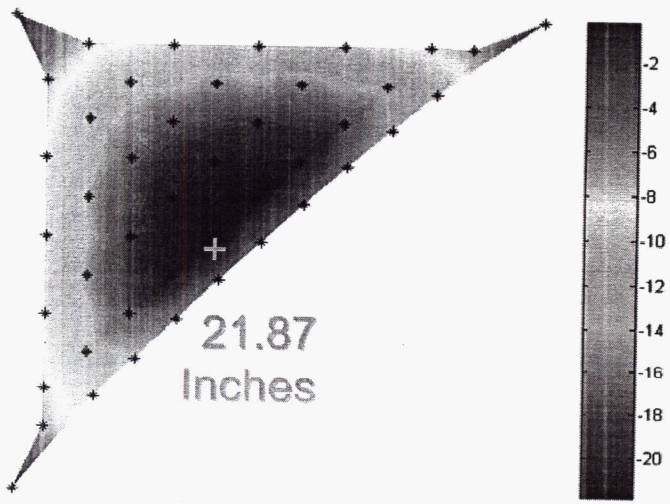
Static Deformation Overview

The Static Deformation for Quadrant 4

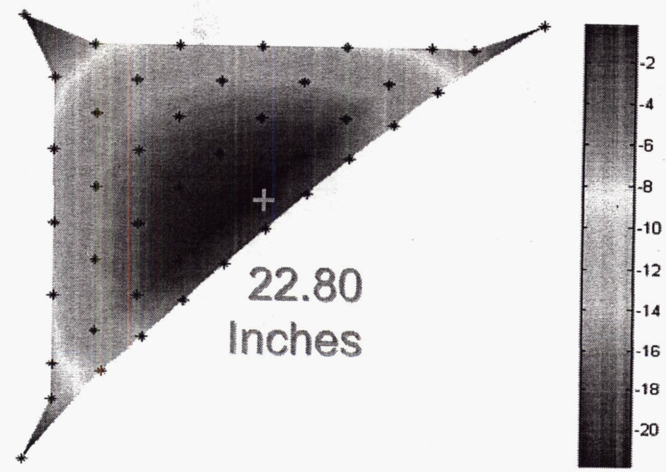
- The 0 degree and 22.5 degree cases were used for the comparisons
- The Photogrammetry (PG) data was transformed to align with global coordinate system
  - The PG data is referenced from points on the structure
  - The center of the coordinate systems are aligned by the hub targets
  - The rotation of the PG coordinate system is aligned by a least squares fit of the boom tip locations
- The analysis was generated using the global coordinate system
  - No transformations were required
  - Only quadrant 4 was included in the analytical model
- The deflection data was compared at the 44 points on the sail

Deflection Shape Comparison – 0 Degrees

PG Deflection Results for Quadrant 4



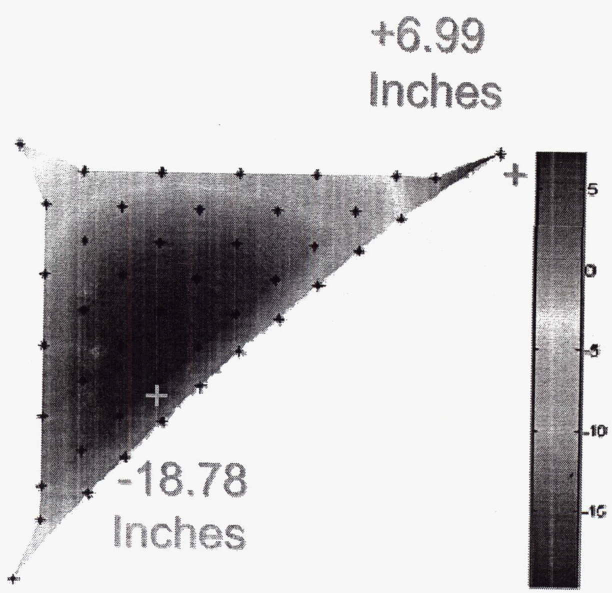
Best Fit Analysis Results for Quadrant 4



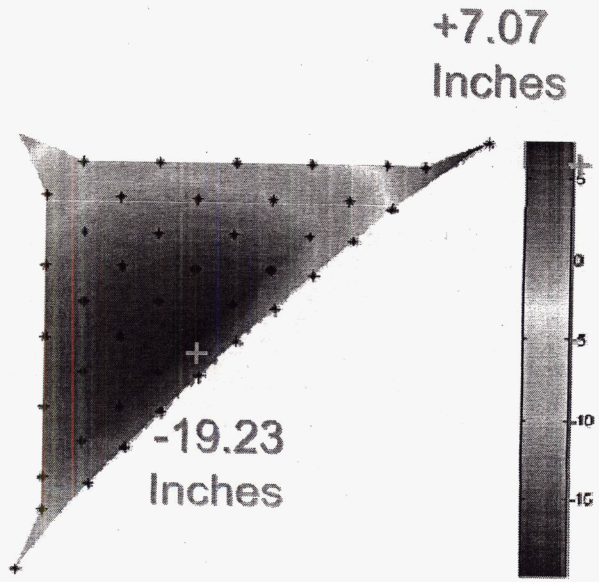
	Test	Analysis	% error
Billow Depth	21.87	22.8	4.3%
Max. Error		0.96	4.4%
RMS Error		0.58	2.7%

- Billow depth was defined in Z-direction of the lowest target
- Max. Error is defined as the max. vertical distance between test and analysis

Deflection Shape Comparison – 22.5 Degrees



PG Deflection Results for Quadrant 4



Best Fit Analysis Results for Quadrant 4

	Test	Analysis	% error
P-P Depth	25.77	26.3	2.1%
Max. Error		1.40	5.4%
RMS Error		0.77	3.0%

- P-P or Peak to Peak depth is the distance from the highest to the lowest target

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System Dynamics Approach

System Dynamics Analysis Proceeded by Steps

- An initial analysis was done with identical sails and tensions
  - The model was based on quadrant 4
  - The model was prepared before the final weighing of the sails
  - A pre-test analysis was performed and the results were provided to the Test Engineer before testing began
- An updated model with individual sail properties was created
  - Each quadrant has independent thickness, weight and modulus
  - Second iteration has updated cord properties as well
  - All halyard loads set at the nominal 6 lbs.
- The final model uses the halyard loads measured during testing
  - The model has fully updated sail properties as above
  - The halyard loads ranged from 4.08 to 6.45 lbs.
- An attempt was made to match the tack line loads instead of the halyard loads
  - The model became increasingly unstable
  - Time constraints prevented obtaining a solution

Boom Dynamics

Test Data Was Used to Tune Boom Dynamics

- Testing was done on the booms without the sails attached
  - The negators holding the boom tips up were locked out
    - A cable still supported the boom tip
    - The boom was free to move horizontally
  - The gravity compensator masses were removed
  - A model was created to reflect these conditions
    - The hub model was included to allow system level boom modes
    - The booms' masses matched the weighed values
- The booms were tuned to match the test frequencies
  - The stiffness of the longerons and diagonals were reduced to match the bending frequencies (~10%)
  - The weights on the tip structure were redistributed to match the torsional frequencies
- Tuned Booms were used in the system dynamics analysis

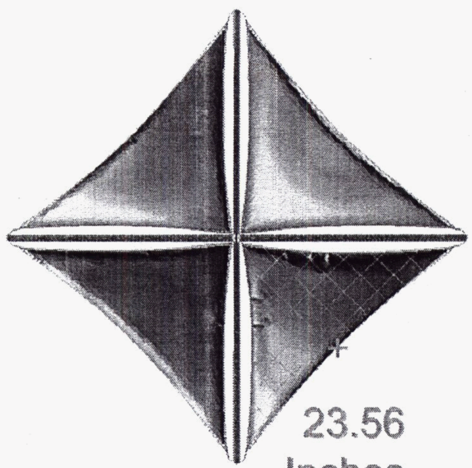
	Test		Baseline		Tuned	
	Min	Max	Min	Max	Min	Max
Horz. Bending	0.797	0.813	0.843	0.845	8.120	8.140
Boom Twist	2.39	2.41	2.20	2.21	2.40	2.40
Vert. Bending	5.14	5.30				
Vert. Bending	7.47	7.87	8.29	8.29	7.77	7.77

System Dynamics

A Number of Challenges for Dynamics Analysis

- The four quadrants had different average tensions
  - This causes asymmetric loading of the booms, bending the booms (model predicts nearly 2 inches)
  - Bending of the booms causes a change in halyard angles
  - Average halyard force for quadrant 4: 6.08 lbs., for quadrant 3: 4.19 lbs.
  - This significantly reduces the stability of the analysis models
- The two halyards on a sail did not have uniform tension
  - This causes an asymmetric loading on the sails
  - Decreases the stability of the analysis models
  - For sail quadrant 1, the discrepancy is 0.83 lbs or 16% of the load
- The sails have different weights
  - Quadrant 1 is 20% lighter (0.816 lbs) than quadrant 4 (1.068 lbs)
  - Produces a torque/twist on the booms
  - Decreases the stability of the analysis models

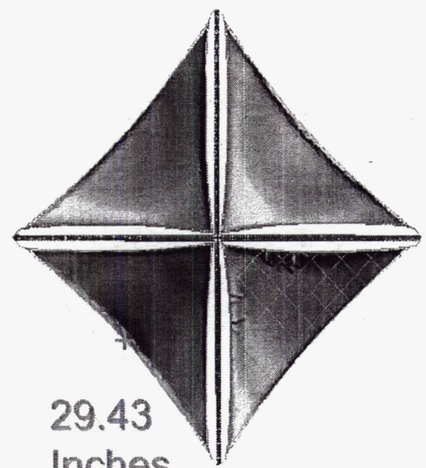
Halyard Tension Effects



Nominal 6 lbs. Halyards

	Boom				
Twist	Vert. Bend	Horz. Bend	Quadrant	1st Sail	2nd Sail
0.51 hz	0.62 hz	1.07 hz	1	1.01 hz	1.54 hz
0.52 hz	0.64 hz	1.15 hz	2	0.99 hz	1.50 hz
0.52 hz	0.64 hz	1.16 hz	3	0.96 hz	1.40 hz
0.53 hz	0.65 hz	1.22 hz	4	0.91 hz	1.46 hz

Min	0.51 hz	0.62 hz	1.07 hz		0.91 hz	1.40 hz
Max	0.53 hz	0.65 hz	1.22 hz		1.01 hz	1.54 hz



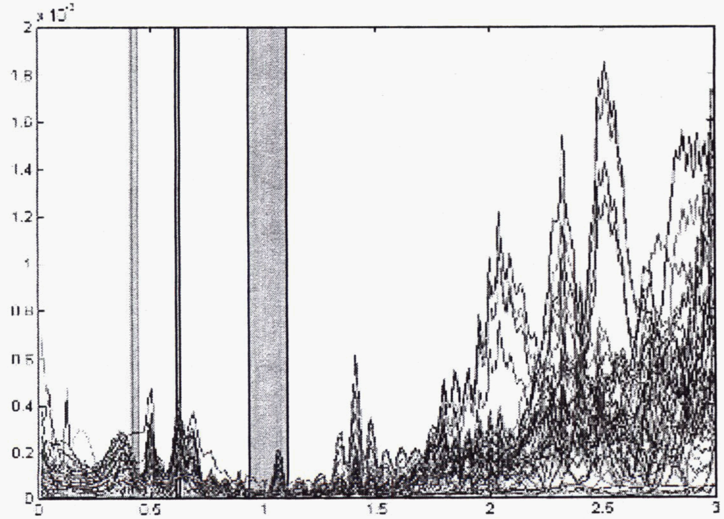
Independent Halyard Tensions

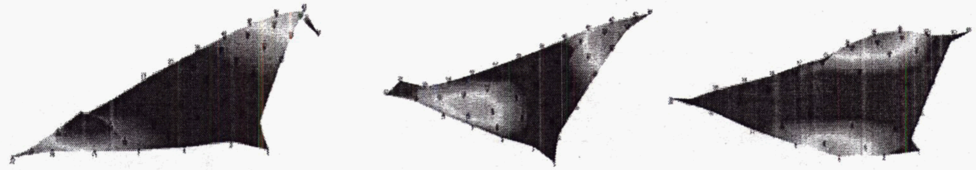
	Boom				
Twist	Vert. Bend	Horz. Bend	Quadrant	1st Sail	2nd Sail
0.42 hz	0.61 hz	0.94 hz	1	0.95 hz	1.45 hz
0.42 hz	0.62 hz	0.99 hz	2	0.97 hz	1.55 hz
0.44 hz	0.62 hz	1.04 hz	3	0.78 hz	1.13 hz
0.44 hz	0.63 hz	1.11 hz	4	0.90 hz	1.49 hz

Min	0.42 hz	0.61 hz	0.94 hz		0.78 hz	1.13 hz
Max	0.44 hz	0.63 hz	1.11 hz		0.97 hz	1.55 hz

- The change in deflection meant significant changes in frequency,
- The modes that were found in the analysis and the test can be divided into two categories.
  - There are modes that are dominated by the behavior of the masts
  - Sails dominated modes.
- Because the masts outweigh the sails by an order of magnitude, the mast-dominated modes created significant motion in the sails.
- The motion and shape of the sail in the mast-dominated modes is determined by the amplitude of the motion of the halyard corners and to the mode proximity to the sail mode.
- Thus for the mast-dominated modes, the frequency is more important than obtaining an exact match in shape.

Analysis Results vs. Test Results

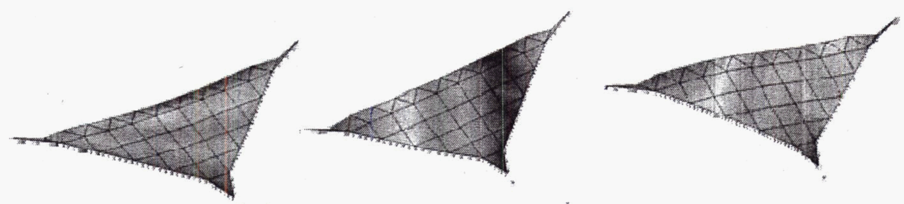




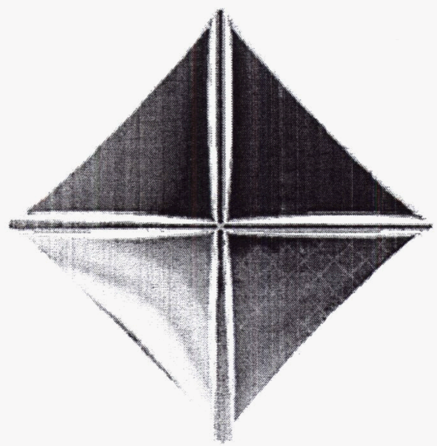
Mod Type	Test Frequency Hz.	Analysis Frequency Hz.	%Difference
Torsion	0.503 Hz	0.412 Hz	18
Vertical Bending	0.625 Hz	0.622 Hz	4
Horizontal Bending	1.06 Hz	0.938 Hz	11.5

Analytic Boom dominated Modes vs. Test

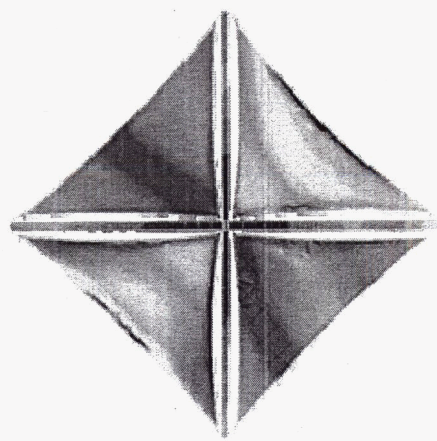
- Analysis shows three groupings of boom modes
  - Torsion like modes around 0.41-0.42 Hz
  - Vertical bending modes at 0.61-0.63 Hz
  - Horizontal bending modes 0.94-1.11 Hz
- Test data shows similar peaks
  - Peaks near 0.5 Hz
  - Peaks around 0.65 Hz
  - Peaks just above 1.0 Hz



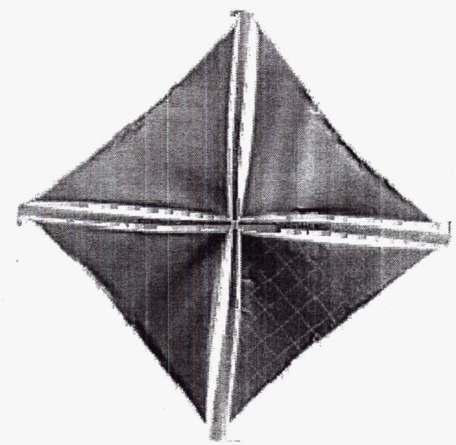
Analytical System Modes - Boom Dominant



0.412 Hz



0.622 Hz



0.938 Hz

Outline

- 20 meter Solar sail FEM
- Mesh Density Study
- Static Shape Optimization
- Static shape test/Analysis correlation and results
- System Dynamics test/analysis comparison
- Summary

Summary

- Conducted Mesh Density study to determine the element type and size that best represents a 20-meter solar sail under ground-test load conditions.
  - TRIA3 elements better represent wrinkle patterns than do QUAD4 elements.
  - Baseline, ten-inch elements are small enough to accurately represent sail shape
  - Baseline TRIA3 mesh requires a reasonable computation time of 8 min 21 sec.
- Performed test/Analysis correlation by using Static Shape Optimization Method for Q4 sail.
  - Ten Parameters Were chosen and Varied During Optimization
  - 300 sail models were created with random parameters
  - A response Surfaces for each targets were created based on the varied Parameters.
  - Parameters were optimized based on response surface.
  - Deflection Shape Comparison for 0 and 22.5 Degrees yielded a 4.3% and 2.1 % error respectively.
- System Dynamic
  - Boom Only
    - Testing was done on the booms without the sails attached
    - The nominal boom properties produced a good correlation to test data the frequencies were within 10%
  - Boom Dominated analysis frequencies and modes compared well with the test results.